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Possible Implications of Small or Large CP Violation in B_d^0 vs $\bar{B}_d^0 \to J/\psi K_{\rm S}$ Decays

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Abstract

We argue that a small or large CP-violating asymmetry $\mathcal{A}_{\psi K_S}$ in B_d^0 vs $\bar{B}_d^0 \to J/\psi K_S$ decays, which seems to be favored by the recent BaBar or Belle data, might hint at the existence of new physics in B_d^0-$\bar{B}_d^0$ mixing. We present a model-independent framework to show how new physics in B_d^0-$\bar{B}_d^0$ mixing modifies the standard-model CP-violating asymmetry $\mathcal{A}_{\psi K_S}^{\rm SM}$. We particularly emphasize that an experimental confirmation of $\mathcal{A}_{\psi K_S} \approx \mathcal{A}_{\psi K_S}^{\rm SM}$ must not imply the absence of new physics in B_d^0-$\bar{B}_d^0$ mixing.

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Recently the BaBar and Belle Collaborations have reported their new measurements of the CP-violating asymmetry in B^0_d vs $\bar{B}^0_d \rightarrow J/\psi K_S$ decays:

$$\mathcal{A}_{\psi K_S} \;=\; \begin{cases} 0.59 \pm 0.14(\text{stat}) \pm 0.05(\text{syst}) \;, & (\text{BaBar} \;\; [1]) \;, \\ \\ 0.99 \pm 0.14(\text{stat}) \pm 0.06(\text{syst}) \;, & (\text{Belle} \;\; [2]) \;. \end{cases} \tag{1}$$

The central values of these two measurements are apparently different from that of the previous CDF measurement, $\mathcal{A}_{\psi K_S} = 0.79 \pm 0.42$ [3]; and they are also different from the result obtained from global analyses of the Cabibbo-Kobayashi-Maskawa (CKM) unitarity triangle in the standard model, $\mathcal{A}^{\rm SM}_{\psi K_S} = 0.75 \pm 0.06$ [4]. In view of the error bars associated with the BaBar and Belle measurements, it remains too early to claim any serious discrepancy between the experimental result and the standard-model prediction. Nevertheless, one cannot rule out the possibility of $\mathcal{A}_{\psi K_S} < \mathcal{A}^{\rm SM}_{\psi K_S}$ or $\mathcal{A}_{\psi K_S} > \mathcal{A}^{\rm SM}_{\psi K_S}$. A small or large CP-violating asymmetry in $B_d \rightarrow J/\psi K_S$ decays should be a clean signal of new physics beyond the standard model.

The purpose of this Brief Report is two-fold. First, we present a model-independent framework to show how new physics in B^0_d-$\bar{B}^0_d$ mixing may modify the standard-model quantity $\mathcal{A}^{\rm SM}_{\psi K_S}$. We find that the possible deviation of $\mathcal{A}_{\psi K_S}$ from $\mathcal{A}^{\rm SM}_{\psi K_S}$ can fully be described in terms of three independent parameters, including the magnitude and phase of the new-physics contribution to B^0_d-$\bar{B}^0_d$ mixing. Second, we point out that the equality $\mathcal{A}_{\psi K_S} = \mathcal{A}^{\rm SM}_{\psi K_S}$ itself must not mean the absence of new physics in B^0_d-$\bar{B}^0_d$ mixing. Indeed there may exist a specific parameter space for the new-physics contribution to B^0_d-$\bar{B}^0_d$ mixing, in which the value of $\mathcal{A}_{\psi K_S}$ coincides with that of $\mathcal{A}^{\rm SM}_{\psi K_S}$. Hence measuring the CP-violating asymmetry $\mathcal{A}_{\psi K_S}$ alone is neither enough to test the standard model nor enough to constrain the possible new physics in B^0_d-$\bar{B}^0_d$ mixing.

It is well known that the CP asymmetry $\mathcal{A}_{\psi K_S}$ arises from the interplay of the direct decays of B^0_d and $\bar{B}^0_d$ mesons, the B^0_d-$\bar{B}^0_d$ mixing in the initial state, and the K^0-$\bar{K}^0$ mixing in the final state [5]:

$$\mathcal{A}_{\psi K_S} \;=\; -{\rm Im} \left(\frac{q}{p} \cdot \frac{V_{cb} V^*_{cs}}{V^*_{cb} V_{cs}} \cdot \frac{q^*_K}{p^*_K} \right) \;, \tag{2}$$

where V_{cb} and V_{cs} are the CKM matrix elements, p and q are the B^0_d-$\bar{B}^0_d$ mixing parameters, p_K and q_K are the K^0-$\bar{K}^0$ mixing parameters, and the minus sign on the right-hand side of Eq. (2) comes from the CP-odd eigenstate $J/\psi K_S$. In this expression the tiny penguin contributions to the direct transition amplitudes, which may slightly modify the ratio $(V_{cb}V^*_{cs})/(V^*_{cb}V_{cs})$ [6], have been neglected. Within the standard model $q_K/p_K \approx 1$, $q/p \approx V_{td}/V^*_{td}$ and $(V_{cb}V^*_{cs})/(V^*_{cb}V_{cs}) \approx 1$ are excellent approximations in the Wolfenstein phase convention for the CKM matrix [7]. Therefore one obtains

$$\mathcal{A}^{\rm SM}_{\psi K} \;\approx\; -{\rm Im} \left(\frac{V_{td}}{V^*_{td}} \right) \;\approx\; \sin 2\beta \;\;, \tag{3}$$

where $\beta \equiv \arg[-(V^*_{cb}V_{cd})/(V^*_{tb}V_{td})] \approx \arg(-V^*_{td})$ is one of the three inner angles of the CKM unitarity triangle [8]. A recent global analysis of the quark flavor mixing data and the CP-violating observables in the kaon system yields $\sin 2\beta = 0.75 \pm 0.06$ [4].

If the measured value of $\mathcal{A}_{\psi K_S}$ deviates significantly from the standard-model prediction in Eq. (3), it is most likely that the B^0_d-$\bar{B}^0_d$ mixing phase q/p consists of unknown new physics contributions. Of course there may also exist new physics in K^0-$\bar{K}^0$ mixing, contributing a non-trivial complex phase to $\mathcal{A}_{\psi K_S}$ through q_K/p_K. It is quite unlikely that the tree-level W-mediated decays of B^0_d and $\bar{B}^0_d$ mesons are contaminated by any kind of new physics in a significant way [9].

To be specific, we assume that a possible discrepancy between $\mathcal{A}_{\psi K_S}$ and $\mathcal{A}^{\rm SM}_{\psi K_S}$ mainly results from new physics in B^0_d-$\bar{B}^0_d$ mixing. We therefore write down the ratio q/p in terms of the off-diagonal elements of the 2×2 B^0_d-$\bar{B}^0_d$ mixing Hamiltonian:

$$\frac{q}{p} \;=\; \sqrt{\frac{M^*_{12} - i\Gamma^*_{12}/2}{M_{12} - i\Gamma_{12}/2}} \tag{4}$$

with

$$M_{12} \;=\; M^{\rm SM}_{12} \;+\; M^{\rm NP}_{12} \tag{5}$$

and $\Gamma_{12} = \Gamma^{\rm SM}_{12}$. Note that $|M_{12}| \gg |\Gamma_{12}|$ is expected to hold both within and beyond the standard model, thus we have $q/p \approx \sqrt{M^*_{12}/M_{12}}$ as a good approximation. The relative magnitude and the phase difference between the new-physics contribution $M^{\rm NP}_{12}$ and the standard-model contribution $M^{\rm SM}_{12}$ are in general unknown. By definition, we may take $|M_{12}| = \Delta M/2$, where $\Delta M = (0.487 \pm 0.014)$ ps^{-1} is the experimentally measured mass difference between two mass eigenstates of B_d mesons [10]. Then we parametrize $M^{\rm SM}_{12}$, $M^{\rm NP}_{12}$ and M_{12} in the following way:

$$\left\{ \begin{matrix} M^{\rm SM}_{12} \\ \\ M^{\rm NP}_{12} \\ \\ M_{12} \end{matrix} \right\} \;=\; \left\{ \begin{matrix} R_{\rm SM} e^{{\rm i}2\beta} \\ \\ R_{\rm NP} e^{{\rm i}2\theta} \\ \\ e^{{\rm i}2\phi} \end{matrix} \right\} \frac{\Delta M}{2} \; , \tag{6}$$

where $R_{\rm SM}$ and $R_{\rm NP}$ are real and positive parameters, θ represents the new-physics phase, and ϕ denotes the effective (overall) phase of B^0_d-$\bar{B}^0_d$ mixing. In this case, $M^{\rm SM}_{12}$, $M^{\rm NP}_{12}$ and M_{12} (or equivalently, $R_{\rm SM} e^{{\rm i}2\beta}$, $R_{\rm NP} e^{{\rm i}2\theta}$ and $e^{{\rm i}2\phi}$) form a triangle in the complex plane, as illustrated by Fig. 1. The dual relation between $R_{\rm SM}$ and $R_{\rm NP}$ can be expressed as

$$R_{\rm NP} \;=\; -R_{\rm SM} \cos 2(\theta - \beta) \pm \sqrt{1 - R^2_{\rm SM} \sin^2 2(\theta - \beta)} \;\; , \tag{7a}$$

and

$$R_{\rm SM} \;=\; -R_{\rm NP} \cos 2(\theta - \beta) \pm \sqrt{1 - R^2_{\rm NP} \sin^2 2(\theta - \beta)} \;\; , \tag{7b}$$

which depends only upon the phase difference $(\theta - \beta)$. There exist two possible solutions for $R_{\rm NP}$ or $R_{\rm SM}$, corresponding to $(\pm)$ signs on the right-hand side of Eq. (7). Numerically, $R_{\rm SM} > 0$ and $R_{\rm NP} \geq 0$ must hold for either solution.

The magnitude of $R_{\rm SM}$ can be calculated in the box-diagram approximation [11]:

$$R_{\rm SM} \;=\; \frac{G^2_{\rm F} \; B_B \; f^2_B \; M_B \; m^2_t}{6\pi^2 \; \Delta M} \; \eta_B \; F(z) \; |V_{tb} V_{td}|^2 \; , \tag{8}$$

where $G_{\rm F}$ is the Fermi constant, B_B is the "bag" parameter describing the uncertainty in evaluation of the hadronic matrix element $\langle B^0_d|\bar{b}\gamma_\mu(1-\gamma_5)d|\bar{B}^0_d\rangle$, M_B is the B_d–meson mass, f_B is the decay constant, m_t is the top-quark mass, η_B denotes the QCD correction factor, V_{tb} and V_{td} are the CKM matrix elements, and $F(z)$ stands for a slowly decreasing monotonic function of $z \equiv m_t^2/M_W^2$ with M_W being the W-boson mass. At present it is difficult to obtain a reliable value for $R_{\rm SM}$, because quite large uncertainties may arise from the input parameters B_B, f_B and $|V_{td}|$. However, $R_{\rm SM}$ is in general expected to be close to unity, no matter what kind of new physics is hidden in B^0_d-$\bar{B}^0_d$ mixing. Note that $R_{\rm SM}=1$ must not lead to $R_{\rm NP}=0$. There is another solution, $R_{\rm NP}=-2\cos 2(\theta-\beta)$ with $\cos 2(\theta-\beta)\leq 0$, corresponding to $R_{\rm SM}=1$. On the contrary, $N_{\rm NP}=0$ must result in $R_{\rm SM}=1$, as indicated by Eq. (7b).

With the help of Eqs. (5) and (6), we recalculate the CP-violating asymmetry $\mathcal{A}_{\psi K_S}$ and arrive at the following result:

$$\mathcal{A}_{\psi K_S} \;=\; \sin(2\phi) \;=\; R_{\rm SM}\sin(2\beta) \;+\; R_{\rm NP}\sin(2\theta) \; . \tag{9}$$

Note that $R_{\rm NP}$, $R_{\rm SM}$, β, and θ are dependent on one another through Eq. (7). Of course, $|\mathcal{A}_{\psi K}|\leq 1$ holds within the allowed parameter space of $R_{\rm NP}$ and θ. The ratio of $\mathcal{A}_{\psi K_S}$ to $\mathcal{A}^{\rm SM}_{\psi K_S}$ is given as

$$\xi_{\psi K_S} \;\equiv\; \frac{\mathcal{A}_{\psi K_S}}{\mathcal{A}^{\rm SM}_{\psi K_S}} \;\approx\; \frac{\sin(2\phi)}{\sin(2\beta)} \;=\; R_{\rm SM} + R_{\rm NP}\frac{\sin(2\theta)}{\sin(2\beta)} \; . \tag{10}$$

In the literature (e.g., Ref. [4]), the value of $\mathcal{A}^{\rm SM}_{\psi K_S}\approx \sin 2\beta$ is obtained from a global analysis of the experimental data on $|V_{ub}/V_{cb}|$, B^0_d-$\bar{B}^0_d$ mixing, B^0_s-$\bar{B}^0_s$ mixing, and CP violation in K^0-$\bar{K}^0$ mixing. The key assumption in such analyses is that there is no new-physics contribution to the K^0-$\bar{K}^0$, B^0_d-$\bar{B}^0_d$, and B^0_s-$\bar{B}^0_s$ mixing systems. If new physics does contribute significantly to the heavy meson-antimeson mixing instead of the light one, one has to discard the direct experimental data on B^0_d-$\bar{B}^0_d$ mixing and B^0_s-$\bar{B}^0_s$ mixing in analyzing the CKM unitarity triangle. In this case, the resultant constraint on $\sin 2\beta$ becomes somehow looser. One may observe, from the figures of the CKM unitarity triangle in Refs. [4,8], that $0.6 \leq \sin 2\beta \leq 0.8$ is a quite generous range constrained by current data on $|V_{ub}/V_{cb}|$ and CP violation in K^0-$\bar{K}^0$ mixing. Given such a generously allowed region for $\mathcal{A}^{\rm SM}_{\psi K_S}$, we conclude that $\xi_{\psi K_S}>0$ is definitely assured. Using $\mathcal{A}^{\rm SM}_{\psi K_S}=0.75\pm 0.06$ [4] for illustration, we obtain

$$\xi_{\psi K_S} \;=\; \left\{ \begin{array}{ll} 0.79 \pm 0.26 \; , & ({\rm BaBar}) \; , \\ \\ 1.32 \pm 0.30 \; . & ({\rm Belle}) \; . \end{array} \right. \tag{11}$$

We see that the BaBar measurement seems to indicate $\xi_{\psi K_S}<1$, while the Belle measurement seems to imply $\xi_{\psi K_S}>1$. If either possibility could finally be confirmed with more precise experimental data from B-meson factories, it would be a very clean signal of new physics [12]. If the further data of both BaBar and Belle Collaborations turn to coincide with each other and lead to $\xi_{\psi K_S}\approx 1$, however, one cannot draw the conclusion that there is no new physics in B^0_d-$\bar{B}^0_d$ mixing.

Now let us show why $\mathcal{A}_{\psi K_S} = \mathcal{A}^{\rm SM}_{\psi K_S}$ must not imply the absence of new physics in B^0_d-$\bar{B}^0_d$ mixing. Taking $\xi_{\psi K_S} = 1$ and using Eq. (7), we obtain the following equation constraining the allowed values of θ:

$$(1 + R_{\rm SM}) \tan^2 2\theta - 2R_{\rm SM} \tan 2\beta \tan 2\theta - (1 - R_{\rm SM}) \tan^2 2\beta \ = \ 0 \ . \tag{12}$$

Then it is straightforward to find out two solutions for $\tan 2\theta$:

$$\tan 2\theta \ = \ \tan 2\beta \ , \tag{13a}$$

or

$$\tan 2\theta \ = \ \tan 2\beta \ \frac{R_{\rm SM} - 1}{R_{\rm SM} + 1} \ . \tag{13b}$$

Note that solution (13a) corresponds to $R_{\rm SM} + R_{\rm NP} = 1$. Solution (13b) implies that $|\tan 2\theta| \ll \tan 2\beta$ may hold, if $R_{\rm SM}$ is remarkably close to 1. Although the afore-obtained region of θ is quite specific, it does exist and give rise to $\xi_{\psi K_S} = 1$. Therefore, an experimental confirmation of $\xi_{\psi K_S} \approx 1$ cannot fully rule out the possibility of new physics hidden in B^0_d-$\bar{B}^0_d$ mixing.

Theoretically, the information on $R_{\rm NP}$ and θ can only be obtained from specific models of new physics (e.g., the supersymmetric extensions of the standard model [12]). An interesting possibility is that the new-physics contribution conserves CP (i.e., $\theta = 0$ [13]) and all observed CP-violating phenomena in weak interactions are attributed to the non-trivial phase in the CKM matrix. In this scenario, we obtain

$$\mathcal{A}_{\psi K_S} \ = \ \sin(2\phi) \ = \ R_{\rm SM} \sin(2\beta) \ . \tag{14}$$

Obviously $\mathcal{A}_{\psi K_S}/\mathcal{A}^{\rm SM}_{\psi K_S} = R_{\rm SM} \leq 1$ is required, in order to understand the present BaBar and Belle measurements.

It becomes clear that the measurement of $\mathcal{A}_{\psi K_S}$ itself is not enough to test the self-consistency of the standard model or to pin down possible new physics hidden in B^0_d-$\bar{B}^0_d$ mixing. For either purpose one needs to study the CP-violating asymmetries in some other nonleptonic B-meson decays, although most of them are not so clean as B^0_d vs $\bar{B}^0_d \rightarrow J/\psi K_S$ decays in establishing the relations between the CP-violating observables and the fundamental CP-violating parameters [14].

In summary, we have discussed possible implications of a small or large CP-violating asymmetry in B^0_d vs $\bar{B}^0_d \rightarrow J/\psi K_S$ decays. While such an effect could be attributed to new physics in K^0-$\bar{K}^0$ mixing, it is most likely to result from new physics in B^0_d-$\bar{B}^0_d$ mixing. Model-independently, we have formulated the basic features of new-physics effects on CP violation in $B_d \rightarrow J/\psi K_S$. We have also pointed out that an experimental confirmation of $\mathcal{A}_{\psi K_S} \approx \mathcal{A}^{\rm SM}_{\psi K_S}$ must not imply the absence of new physics in B^0_d-$\bar{B}^0_d$ mixing. An extensive study of all hadronic B-meson decays and CP asymmetries is desirable, in order to test the standard model and probe possible new physics at some higher energy scales.

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FIGURES

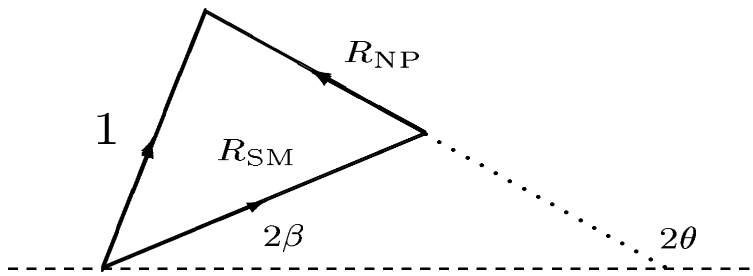

FIG. 1. Triangular relation of $M_{12}^{\rm SM}$, $M_{12}^{\rm NP}$ and M_{12} (rescaled by $\Delta M/2$) in the complex plane.